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Investigating performance improvement of solar collectors by using nanofluids

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ABSTRACT

The present review is an extensive perspective of the research progress arisen in the performance of solar collector using nanofluids. The increase in the price of fossil fuels and rapid depletion of conventional energy sources are among the major energy concerns. Solar collector, as a kind of green and renewable energy device, can help us stay out of these energy concerns. Low efficiency and high cost of solar collectors compared with the conventional devices persuade scientists and engineers to make effort to increase performance of solar collectors. Nanofluid – the suspension of nanoparticles into a basefluid – has predominant characteristics because of nanoparticles' small size and high surface area. Many researchers evaluated these special properties of nanofluids, using several methods and techniques. Mathematical and numerical methods are practiced and experimental methods come to validate the results. Using nanofluid instead of conventional fluid improves heat transfer as well as optical and thermal properties, efficiency, transmittance and extinction coefficient of solar collector. Based on comprehensive studies, it has been also realized that the thermal properties of nanofluid such as thermal conductivity have significant effect on improving the efficiency of direct solar absorption collectors. On the other hand, using nanofluid is a big challenge in terms of economical aspects. Moreover, there is a lack of study on the effect of nanofluid's optical properties such as transmittance and extinction coefficient on the performance of solar collector. Similarly, effort should be made to perform two-phase analysis of nanofluid and study properties of nanofluid with more than one type of nanoparticle.

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Nomenclature

A_{abs}	areas of absorber surface, m^2
A_{ap}	area of aperture that admit or receive radiation, m^2
A_m	solar-weighted absorption coefficient
C_p	specific heat of fluid, kJ kg^{-1} K^{-1}
D	diameter of the particle, nm
E_λ	solar incident per unit wavelength
F_m	collector parameter
e_c	specific flow exergy of collector, J kg^{-1}
f_v	volume fraction, %
I	insulation, W s^{-2}, Eq. (19)
I_{DN}	direct irradiation, W m^{-2}
$I_{t\theta}$	total irradiation of collector, W m^{-2}
$\dot{I}$	local solar radiation per unit of area, W m^{-2}
k	complex component of the refractive index
m	solar air mass
$\mathbf{m}$	relative complex refractive index of the nanofluid
$\dot{m}$	fluid flow rate, kg s^{-1}
$\dot{Q}$	useful heat, *w*
Q_{abs}	absorption efficiency
Q_{ext}	extinction efficiency
Q_{scat}	scattering efficiency
q_u	useful heat gained by collector, W m^{-2}
T_{amb}	ambient temperature, °C
T_c	collector temperature, °K, Eq. (13)
T_{in}	inlet temperature, °C
T_m	fluid leaving collector temperature, °C
T_{out}	outlet temperature, °C
T_0	ambient temperature, °K, Eq. (13)
t_a	temperature of atmosphere, °C
t_{abs}	temperature of absorber, °C
t_{fe}	temperature of fluid leaving collector, °C
t_{fi}	temperature of fluid interring collector, °C
t_p	temperature of absorber plate, °C
U_L	upward heat loss coefficient, W m^{-2} K
x	thickness of the fluid layer
α	size parameter, nm, Eq. (8)
α	absorptance, Eqs. (2) and (3)
θ	incident angle
ρ	reflectance of concentrator surface
τ	transmittance
σ	Stefan–Boltzman constant, $5.67*10^{-8}$ Wm^{-2} k^{-4}.
σ	extinction coefficient
η	efficiency
η_{EXP}	experimental efficiency
η_{MOD}	model efficiency
λ	wavelength of the incident light, nm
Γ	fraction of reflected or refracted radiation

1. Introduction

After industrial revolution (1970s) energy consumption increased sharply, so threat of energy shortages led scientists to find new sources of energy [1,2]. During past decades, the price of fossil fuels has increased dramatically. Due to this increasing and harmful effect of using fossil fuels on the environment, renewable energy, especially solar energy, should be given more attention than what has been given before. Solar energy, unlike conventional fossil fuels, is generally available at every place on the Earth. Since it is plentiful and the least expensive to implement, this source of energy has been used widespread around the world [3–5]. It is also used in different applications including solar electricity, air-conditioning, cooker and water heater [6]. Solar collector as a solar energy recovery device recovers the energy of sun and converts it to heat. It includes solar water heater and solar air heater that produce hot water and air respectively. It can be stated that solar collectors convert solar radiation into heat. Solar radiation, which includes high amount of energy, can conduct the energy of the sun through photons to the fluid [7]. It has been shown that solar collectors have a significant role in reducing energy consumption.

Nano-science has a very important role in promoting technology. Nanofluid (liquid nanocomposite) is a mixture of a liquid substance (basefluid) and nanometer-sized material (nanoparticle) [8,9]. Nanofluids have intensified thermophysical properties such as viscosity, thermal diffusivity, thermal conductivity, and convective heat transfer coefficients compared to conventional fluids [10]. A new and simple way to improve performance of solar collectors is to use nanofluid in place of conventional heat transfer fluid [11]. For example, this method has significant effect on increasing thermal conductivity even up to two times in some cases by using less than 1% volume of nanoparticle [12]. Presently, different kinds of nanoparticle are used in nanofluids such as

- oxide ceramics (Al_2O_3, CuO),
- metal carbides (Sic),
- nitrides (An, Sin),
- metals (Al, Cu),
- nonmetals (Graphite, carbon annotates),
- layered ($Al+Al_2O_3$, Cu+C),
- PCM (S/S),
- functionalized nanoparticle.

Materials for basefluid include

- water,
- ethylene glycol and other coolants,
- oil and other lubricants,
- bio-fluids,
- polymer solutions,
- other common fluids.

Adding nanoparticle into basefluid can augment the thermo-physical properties of fluid such as thermal conductivity [13–16], mass diffusivity [17] and radiative heat transfer [18,19] as a result of small size and thermophysical properties of nanoparticles. According to a recent research [20] nanoparticle volume fraction has significant effect on direct solar collector efficiency. It has been found that by increasing aluminum nanoparticle to water, as basefluid, the collector efficiency is increased. Nevertheless, the particle size has no significant effect on the collector efficiency.

This paper investigates the effects of using nanofluids on the performance of solar collectors. Solar collectors contain a working fluid that acts as thermal energy absorber and heat transfer medium. Therefore, using nanofluid as the working fluid of solar collector can change the performance, thus leading to higher efficiency.

2. Nanofluid effective properties on the performance

Long-term stability of nanoparticle dispersion is one of the important characteristics of nanofluids. Thermal conductivity is influenced by stability of nanofluids. Higher thermal conductivity

occurs when the nanofluid is at a higher level of stability [21]. However, the dispersion characteristic of the nanoparticle is affected by the duration or length of time. After a long period of time nanoparticles may tend to agglomerate [22]. The tendency of nanoparticle to agglomerate into larger particles is one of the difficulties in production of nanofluids. This causes less surface area and creates a distance from the special properties of nanoparticle. To counteract this tendency, additives are used to expedite the dispersion of the nanoparticles. However, this additives make impurities that can change properties of the basefluid [23]. Stability and durability are the two significant prerequisites of a nanofluid.

Different materials like metal oxides, and non-metal nanoparticles can be added into basefluids such as water, ethylene glycol, or oils with or without surfactant [24]. Based on the Stokes law, Eq. (1), the speed of nanoparticle's sedimentation can decrease by decreasing the nanoparticle size (R), raising the basefluid viscosity (μ), and decreasing the density difference between the nanoparticle and basefluid ($\rho_p - \rho_f$). But the most significant factor is R, therefore according to the Brownian motion of nanoparticle, the sedimentation will be zero if the particle size reach the critical size (R_c) [24].

$$V = \frac{2R^2}{9\mu}(\rho_p - \rho_f) \quad (1)$$

Two common methods used to produce nanofluid are single-step and two-step techniques [24,25]. In the single-step method, the preparation of nanoparticle and synthesis of nanofluid are done in one step. Hence, the nanofluid has a higher stability and a lower agglomeration. In the two-step method, drying nanoparticles are produced and stored in a suitable liquid. However, sedimentation occurs because of the nanoparticle's high surface energy. Therefore, this method is challenging. The level of stability is examined by instruments such as UV–vis spectrophotometer, zeta potential, sediment photograph capturing, Transmission Electron Microscopy (TEM), Scanning Electron Microscopy (SEM). Methods such as light scattering, three omega and sedimentation balance methods are utilized to classify the relative stability of nanofluid [24].

Choi et al. [26] urged to control the addition of the surfactant, because they found that the excess additives have a destructive effect on the thermal properties, viscosity and chemical stability. This creates physical and/or chemical instability problems.

Density and viscosity are two properties of nanofluids that can influence the pressure drop of a fluid. These two properties are proportional to nanoparticle volume fraction. An increase in viscosity and density leads to a higher-pressure drop as compared with basefluid. This pressure drop increases the pumping power [22].

Lee et al. [27] and Yu et al. [28] revealed that the viscosity of nanofluid is higher than basefluid, also the numerical study [29] shows that the density of basefluid increases by adding nanoparticles.

3. Performance of solar collector using nanofluids

In steady state, the performance of a solar collector is described by an energy balance. Energy balance points out the distribution of incident solar radiation into useful energy gain, thermal losses and optical losses. Thermal energy is lost from the collector to the surroundings by conduction, convection and infrared radiation [30].

The performance of solar collector may be analyzed by a procedure originated by Hotteland Woertz [133] and extended by ASHRAE [31]. The basic equation is

$$q_u = I_{t\theta}(\tau\alpha)_\theta - U_L(t_p - t_{at}) = \dot{m}c_p(t_{fe} - t_{fi})/A_{ap} \quad (2)$$

Eq. (2) may also be conformed for concentrating collectors [31]:

$$q_u = I_{DN}(\tau\alpha)_\theta(\rho\Gamma) - U_L(A_{abs}/A_{ap})(t_{abs} - t_a) \quad (3)$$

To achieve high performance, solar collector should boost up the absorption from the sun. It should also increase heat transfer rate to the fluid and from the fluid to the end user. In addition, it should decrease heat losses to the surrounding such as reflection of sun radiation, radiation from hot surface of the system, and heat transfer from the system to the surrounding. These points will be discussed in the following sections.

Knowing the transmission, reflection, and absorption of the several parts of a solar collector, it is vital in finding collector performance. The transmittance, reflectance, and absorption are functions of the incoming radiation, thickness, refractive index, and extinction coefficient of the material. Generally, the refractive index (n) and the extinction coefficient (K) of the cover material are functions of the wavelength of the radiation. Glass is the most popular cover material. Some cover materials have significant variations in optical and spectral property with wavelength [30].

Some external items, like condensation, moisture and unfavorable weather, can reduce the performance of evacuated tube collectors. Collector's absorbing plate should be selected with high value of solar radiation absorbance (α) and low value of longwave emission (e) [7].

Similar to the performance of photovoltaic cell, dust and shading have important effects on the solar collector's performance depending on the angles of incident light, climatic conditions, collector structure and glass dirt [30,32].

The performance of solar collectors can be estimated by using many famous computer programs, such as TRANSYS [33], MINSUN [33–36], WATSUN [37]. These are types of General-Purpose Programs with Sequential Modular Approach [38]. Metrological data that is used in these programs may be created by model based time-series synthesizers that utilize long-run databases, like METEONORM, TMD, TMY [39], or any other databases for the specific area where the simulation is executed [40].

There are different testing standards to characterize the collector performance, such as ASHRAE-93:2003 [41] and EN-12975:2006, which are employed in the USA and European countries, respectively. The EN-12975 standard describes the flat plate collector testing system in steady state or in quasi-dynamic regimes [42].

3.1. Optical properties

The ratio of the speed of light in a vacuum to medium is defined as the refractive index. The real part of the refractive index (n) is known, but the imaginary part of the refractive index (k) is not known for many fluids. The typical techniques for appraisal of the optical constants are [43–45] as follows:

1. Practice of Snell's law to conclude n and measuring the refraction angles (requires $k=0$);
2. Measurement of transmittance and reflectance for a slab at near-normal incident.
3. Measurement of the reflectance over a wide spectral rang and then application of the Kramers–Korning analysis (requires extrapolation and extended measurement).
4. Ellipsometry.
5. Reflectance measurements at various polarizations and incident angles (requires large angles and sample sizes).

Otanicar et al. [46] investigated the optical properties of four fluids (water, propylene glycol (PG), ethylene glycol (EG), and

Therminol VP-1). Generally, these fluids are used as the basefluid for direct absorption receivers. Experimentally, they measured transmittance spectra for all four fluids, and they have found strong absorption bands at 950–1000 nm and at 1200 nm for water, *EG* and *PG*. A significant amount of solar energy is concentrated in the visible band (300–700 nm). In addition, they have found that the water as basefluid is the strongest solar energy absorber (however, it is not high enough, absorbing only 13% of solar energy). According to this paper in order to increase solar-weighted absorption coefficient to more than 90%, the fluid depth should increase to 1.0 m or larger. The solar-weighted absorption coefficient (A_m) describes the proportion of solar energy that is absorbed across a fluid layer of selected thickness [46,47] and is defined by [30]

$$A_m = \frac{\int E_\lambda(1-e-4^{\pi k x/\lambda})d\lambda}{\int E_\lambda d\lambda} \tag{4}$$

Based on the results in the literatures, absorption of the incident radiation increases within the fluid by adding small particles into the basefluid [46]. By using nanoparticles the optical properties of basefluid dramatically increases [19]; it is mentioned that the absorption of incident radiation increases by more than nine times, using nanoparticles instead of pure water. Therefore, many researchers have decided to apply nanofluid in their work [20,48]. The optical properties of the fluid is a function of particle size, particle shape, and the optical properties of the particle and basefluid [49].

3.1.1. Transmittance

The transmission is one of the factors that can affect the collector's performance. Glass, the material most commonly used as a cover material in solar collectors, may absorb a little of the solar energy spectrum if its Fe_2O_3 content is low. If its Fe_2O_3 content is high, it will absorb the infrared portion of the solar spectrum. Low iron glass has the best transmission; glass with high Fe_2O_3 content has a greenish appearance and is a relatively poor transmitter [30].

The glazing is used to increase solar radiation admission and reduce the upward loss of heat as much as possible. Antireflective coating and surface texture are two parameters that can enhance transmission. Dirt and dust may have quite small effect on collector glazing. The washing effect of occasional rain is sufficient to keep the transmittance in a good condition within 2–4% of its highest value [7].

According to Eqs. (2) and (3), maximum performance occurs in high transmittance (τ) of glazing and high absorptance (α) of absorber plate. In case of direct solar absorption collectors, the transmittance and absorptance of fluid are also considered. Maximum absorptance and minimum transmittance are desirable. Adding nanoparticle to the basefluid improves absorption by increasing the scattering of the incident radiation within the fluid [46]. Since the summation of reflected, absorbed, and transmitted radiation is unity, by increasing absorptivity and maintaining the reflectivity, the transmittance decreases [50]. Therefore, nanofluid plays an effective role in direct absorption solar thermal systems by improving energy absorption from incident light and enhancing heat transfer through nanofluid to the end user.

3.1.2. Extinction coefficient

The energy of incident beam is decreased due to the absorption and scattering of light. The amount of this reduction equals the absorbed and scattered energy that is called extinction [51].

The extinction coefficient of an individual particle is a combination of the absorption and scattering coefficients. Both of them are functions of the relative complex refractive index of the nanofluid (m), and the particle size parameter (α), shown in the following equations:

$$Q_{ext} = Q_{scat} + Q_{abs} \tag{5}$$

$$Q_{scat} = \frac{8}{3}\alpha^4\left|\frac{m^2-1}{m^2+2}\right|^2 \tag{6}$$

$$Q_{abs} = 4\alpha \mathrm{Im}\left\{\frac{m^2-1}{m^2+2}\left[1+\frac{\alpha^2}{15}\left(\frac{m^2-1}{m^2+2}\right)\frac{m^4+27m^2+38}{2m^2+3}\right]\right\} \tag{7}$$

$$\alpha = \frac{\pi D}{\lambda} \tag{8}$$

However, Q_{scat} is at least one order of magnitude smaller thanQ_{abs}, accordingly the scattering is usually neglected. Therefore, the extinction coefficients of the basefluid and nanoparticle are calculated from the following equations [44]:

$$\sigma_{basefluid} = \frac{4\pi k_{basefluid}}{\lambda} \tag{9}$$

$$\sigma_{particles} = \frac{3 f_v(Q_{scat}+Q_{abs})}{2\quad D} \approx \frac{3 f_v Q_{abs}}{2\quad D} \tag{10}$$

$$\sigma_{total} = \sigma_{basefluid} + \sigma_{particles} \tag{11}$$

Based on the equations above, the extinction coefficient of nanofluid is a function of the diameter of the particle (D), volume fraction (f_v), refractive index (k), and the wavelength of the incident light (λ). Generally, the extinction coefficient of the nanofluid is considered, when the fluid is in contact with light. In typical solar collectors, the light has no direct contact with fluid, so changing fluid has no effect on the total extinction coefficient of the device. However, according to the above equations in direct absorb solar collector, absorption coefficient increases by using nanoparticles and as a result, the extinction coefficient increases. Therefore, according to the basic equations (2) and (3), absorption of incident light increases and consequently the performance of solar collector improves.

Single-wall carbon nanohorn (SWCNH) in ethylene glycol, as a new nanofluid for solar thermal application, is reported by Sani et al. [52]. The optical properties were measured experimentally and compared with glycol-based amorphous carbon suspension, which is a more conventional commercial carbon form. The results show the photonic properties improvement of SWCNHs-based nanofluid can lead to a significant increase in the light extinction level even at very low concentration. The optical investigation of this nanofluid can provide useful information for the design of direct solar collectors. The experimental and theoretical investigation on evaluation of the optical properties of a new working fluid (Graphite, Al, Cu, Ag, Au/Therminol VP-1, Water) has been done by Taylor et al. [44]. The results of this study reveal that around 95% sunlight absorption can be achieved (in a nanofluid depth ≥10 cm) with 0.001 vol% nanofluid. The absorption at shorter wavelengths is mostly due to the nanoparticles and at longer wavelengths is due to the base fluid. Despite significant improvement in optical properties of nanofluid as an important parameter to evaluate performance of direct solar collectors, further in-depth investigations are needed in order to evaluate the actual effects of suspended nanoparticles on the performance of solar collector due to the optical properties of nanofluid.

3.2. Thermal properties

Thermal losses are one of the important parameters to evaluate the efficiency of solar collectors. In solar collector systems, heat is wasted in two ways: in the device and between device and users. In the device, it can be through the absorber plate to the upper side and through the absorber plate to the back surface of the box. The

heat loss to the upper side is comprised of five mechanisms: (1) the convection loss due to free convection in air passage between the absorber plate and the parallel glass cover, (2) the radiative loss between the glass cover and the absorber plate, (3) the conductive loss across the glass cover, (4) the radiative loss between sky and the glass cover, and (5) the Buoyancy-driven free and forced convection on the glass cover of the collector due to wind. The heat loss to the back surface takes place due to conductive loss across the box's back surface and the insulation, and Buoyancy-driven free and forced convection at the box's back surface. Meanwhile, the lateral thermal loss is negligible [40]. The main wasted heat between collector and users is the wasted heat through the fluid transmission pipe to the surrounding. However, it should be noted that the thermal efficiency increases by decreasing losses and/or increasing by heat transfer to the fluid and finally the end users. Therefore, a way to increase efficiency of solar collector system is to improve thermal properties of fluid to transfer maximum heat to the end users. In order to achieve higher thermal properties and lower heat losses, fluids with suspension nanoparticle were considered.

Adding small amount of nanoparticles can change the properties of basefluid, especially showing improvement in the thermal properties [53]. Wang et al. [134] and Trisaksri et al. [48] have used nanoparticles to enhance the thermal characteristics of colloidal suspension [46]. Thermal conductivity of nanofluids is a function of both basefluid and nanoparticles. By increasing the thermal conductivity of basefluids and/or nanoparticles, the thermal conductivity of nanofluids increases [22,54]. The ratio between surface and volume of nanoparticle is called surface to volume ratio. It is increased by decreasing the size of nanoparticles. The effect of surface to volume ratio on thermal conductivity of nanofluids is rather more than thermal conductivity of nanoparticles [22,55].

The most effective parameters in increasing thermal conductivity of nanofluids are particle concentration, temperature, and particle size [56,57] dispersion and stability [22]. Thermal conductivity is also affected by particle volume fraction, particle polydispersity, and elapsed time. It has been noticed that by increasing particle volume fraction, thermal conductivity will increase; however, it decreases when the time has elapsed [22]. Furthermore, level of acidity (PH) and surfactant that is used to improve stability are effective [27].

Other parameters that can have an effect on effective thermal conductivity include dispersion of the suspended particles, intensification of turbulence, Brownian motion, thermophoresis and diffusiophoresis [53]. Based on the literature, the specific heat of nanofluids is lower than that of basefluid [22].

Suspended nanoparticles affect thermal conductivity and the convection heat transfer coefficient of the fluid greatly [58–61]. Shen [62] reported that the thermal conductivity of metallic and non-metallic nanofluids is improved compared with basefluid.

The thermal conductivity enhancement for various particle sizes and volume fractions of metallic and non-metallic nanofluids is tabulated in Table 1. The nanofluids' thermal conductivity ratio (i.e. thermal conductivity of solid to liquid) is found in Table 2 [22].

Table 2
Thermal conductivity ratio of different types of nanofluid (adapted from [22]).

Nanoparticle	k_2/k_1 [a]	Fluid
SiO_2	5.2	Ethylene glycol
TiO_2	33.0	Ethylene glycol
ZnO	113.0	Ethylene glycol
$A1_2O_3$	156.0	Ethylene glycol
CuO	300.0	Ethylene glycol
Fe	311.0	Ethylene glycol
Cu	1550.0	Ethylene glycol,
Diamond	3500.0	Ethylene glycol
Au	1830.0	Ethanol
$A1_2O_3$	140.0	Glycerol
Carbon nanofibers	111.0	Oil
$A1_2O_3$	342.0	Oil
Graphite	1020.0	Oil
Carbon nanotubes	14300.0	Oil
Carbon nanofibers	3.0	Toluene
Au	2370.0	Toluene
SiO_2	2.2	Water
Fe_3O_4	11.5	Water
TiO_2	14.0	Water
Carbon nanofibers	21.0	Water
ZnO	48.0	Water
$A1_2O_3$	66.0	Water
CuO	127.0	Water
Fe	132.0	Water
Au	518.0	Water
Cu	655.0	Water
Ag	697.0	Water
Carbon nanotubes	3290.0	Water

[a] k_1, thermal conductivity of liquid; k_2, thermal conductivity of solid.

Table 1
Summary of thermal conductivity of nanofluid (adapted from [62]).

	Particle	Basefluid	Average particle size	Volume fraction	Thermal conductivity enhancement
Metallic nanofluids	Cu	Water	100 nm	7.50%	78%
	Cu	Ethylene glycol	10 nm	0.30%	40%
	Au	Water	10–20 nm	0.03%	21%
	Fe	Ethylene glycol	10 nm	0.55%	18%
	Ag	Water	60–80 nm	0.00%	17%
	MWCNT[a]	Synthetic oil	25 nm in diameter 50 μm in length	1%	150%
	MWCNT	Water	100 nm in diameter 70 μm in length	0.60%	38%
Non-metallic nanofluids	Al_2O_3	Water	13 nm	4.30%	30%
	TiO_2	Water	15 nm	5%	30%
	Al_2O_3	Water	68 nm	5%	21%
	MWCNT	Decene–ethylene glycol–water	15 nm in diameter 30 μm in length	1%	20–13–7%
	CuO	Water	50 nm	0.40%	17%
	SiC	Water	26 nm	4.20%	16%
	Al_2O_3	Water	33 nm	4.30%	15%
	CuO	Water	36 nm	3.40%	12%

[a] MWCNT, multi-walled carbon nanotube.

Table 3
Summary of the experimental studies on convective heat transfer of nanofluid.

Author	Basefluid	Particle material	Particle size	Volume fraction (vol%)	Dimension	Flow regime, *Re*	Results and remarks
Pak and Cho [70]	Water	g Al_2O_3 TiO_2	13 nm 27 nm	1–3 1–3	ID = 1.066 cm Length: 480 cm S.S. tube	*Re* = 104–105 (turbulent flow)	*Nu* increased with increase in *w* and *Re*
Eastman et al. [71]	Water	CuO	< 100 nm	0.9	–	(Turbulent flow conditions)	HTC increased by > 15% compared with pure water
Xuan and Li [72]	Water	Cu	< 100 nm	0.3, 0.5, 0.8, 1, 1.2, 1.5, 2	ID = 10 mm Length = 800 mm Brass tube	*Re* = 10,000–25,000 (turbulent flow)	Convective HTC increases with increase in *w* and flow velocity
Xuan and Li [73]	Water	Cu	26 nm	0.5, 1, 1.5, 2	Hydraulic *D* = 1.29 mm	*Re* = 200–2000 (laminar flow)	Nu of nanofluid with *w* = 2% is 39% more than pure water
Wen and Ding [74]	Water	g Al_2O_3	26–56 nm	0.6, 1, 1.6	ID = 4.5 mm Length = 970 mm Copper tube	*Re* = 500–2100 (laminar flow)	For *w* = 1.6%, the HTC is 41% higher than the basefluid
Zhou [75]	Acetone	Cu	80–100 nm	0.0–4.0 g/l	ID = 16 mm Length (*L*) = 200 mm Copper tube	–	Convective heat transfer coefficient (HTC) increases with addition of Cu nanoparticles
Faulkner et al. [76]	Water	CNT	< 100 nm	1.1, 2.2, 4.4	Hydraulic *D* = 355 μm	*Re* = 2–17 (laminar flow)	HTC was found to be high at higher concentrations
Xuan and Li [77]	Water	Cu	26 nm	0.5, 1, 1.5, 2	ID = 10 mm Length = 800 mm Brass tube	*Re* = 1000–4000 (laminar and turbulent flow)	*Nu* ratio varied from 1.06 to 1.39 when *w* increases from 0.5 to 2%
Yang et al. [78]	Oil	Graphite	20–40 nm	0.7–1.0	ID = 4.57 mm Smooth tube	*Re* = 5 < 110 (laminar flow)	HTC was 22% higher at 50 °C and 15% higher at 70 °C for 2.5 wt%.
Lai et al. [79]	Water	Al_2O_3	20 nm	0–1	ID = 1 mm S.S. tube	*Re* < 270	*Nu* enhancement of 8% for *w* = 1% $A1_2O_3$ nanofluid at *Re* = 270
Ding et al. [80]	Water	MWCNT	100 nm	0.1–1.0 wt%	ID = 4.5 mm Length = 970 mm Copper tube	*Re* = 800–1200 (laminar flow)	350% enhancement was found for 0.5 wt% at *Re* = 800
Heris et al. [81]	Water	Al_2O_3 CuO	20 nm 50–60 nm	0.2–3.0 0.2–3.0	ID = 6 mm Copper tube	*Re* = 650–2050 (laminar flow)	- HTC was high when w increases for $A1_2O_3$, Nu is high
Esfahany et al. [82]	Water	g Al_2O_3	20 nm	0.2, 0.5, 1, 1.5, 2, 2.5	ID = 6 mm Length = 1 m Copper tube	*Re* = 700–2050 (laminar flow)	HTC ratio increases with *w* and 22% increase with *Pe*
Yulong et al. [83]	Ethylene glycol	TiO_2 CNT	–	–	–	–	Convective HTC increases with *w* and *Re*
Zeinali Heris et al.[82]	Water	Al_2O_3	–	0.2, 0.5, 1, 1.5, 2, 2.5	1 m annular tube Copper tube ID = 6 mm	*Re* = 700–2050 laminar flow	Heat transfer coefficient increase with Peclet number
Williams et al. [84]	Water	ZrO_2	46 nm 60 nm	0.9–3.6 0.2–0.9	OD: 1.27 cm Thick = 1.65 mm S.S. tube	9000 < *Re* < 63000 (turbulent flow)	Considerable heat transfer enhancement is observed
Jung et al. [85]	Water	Al_2O_3	l0 nm	0.5–1.8	Rectangular microchannel (50 μm_50 μm)	5 < *Re* < 300	Conv. HTC increased by 32% for *w* = 1.8%. Nu increases with *Re*

Table 3 (*continued*)

Author	Basefluid	Particle material	Particle size	Volume fraction (vol%)	Dimension	Flow regime, *Re*	Results and remarks
Fotukian and Nasre Esfahany [86]	Water	g Al_2O_3	20 nm	0.03, 0.054, 0.067, 0.135	Straight copper tube ID=5 mm	Re=6000–31,000	Heat transfer improvement
Fotukian and Nasre Esfahany [87]	Water	CuO	30–50 nm	0.015, 0.031, 0.039,0.78,0.118 0.157, 0.236	1 m annular tube Cooper tube ID=5 mm	Re=6000–31,000	−25% increase in HTC −20% pressure drop penalty −Increase flow resistance
Sajadi and Kazemi [88]	Water	TiO_2	30 nm	0.05, 0.1, 0.15, 0.20, 0.25	Straight copper tube ID=5 mm L=1800 mm t=0.675 mm	Re=5000–30,000	Heat transfer improvement with nanoparticle volume fraction increase Higher pressure drop to compare with base fluid
Kayhani et al. [89]	Water	TiO_2	15 nm	0.1, 0.5, 1.0, 1.5 ,2.0	Circular tube ID=5, OD=6 mm L=2 m	Re=6000–16,000	Increases HTC with increased nanofluid volume fraction and no change with Re
Akhavan-Behabadi et al. [90]	Oil	MWCNT	OD: 5–20 ID: 2–6 nm L=1–10 μm	0.1, 0.2, 0.4 wt%	Helically coiled tube		Too high Nusselt number compared with base fluid. Increased heat transfer rate with mass concentration or Re

It is obvious that metals have higher conductivity than fluids at room temperature. For instance, thermal conductivity of Silver is about 700 times more than water and carbon nanotube is about 14000 times more than engine oil, and SiO_2 is just 5 times greater than ethylene glycol. Metallic liquids have higher thermal conductivities than non-metallic liquids [63].

Four mechanisms including Brownian motion of the nanoparticles, molecular-level layering of the liquid at the liquid/particle interface, the heat transfer features of the nanoparticles, and the effects of nanoparticle clustering are proposed by Keblinski et al. [61] and Eastman et al. [71] to elucidate the reason of the abnormal increase of the thermal conductivity. To explain the reason for the increase of the effective thermal conductivity Xuan and Li [91] introduce five possible reasons: the increase in surface area due to suspended nanoparticles, the increase in thermal conductivity of fluid, the interaction and collision among particles, the intensified mixing fluctuation and turbulence of the fluid, and the dispersion of nanoparticle [64].

3.3. Heat transfer

Conduction, convection, and radiation are three types of heat transfer that are considered in a solar collector; however, accurate calculations of the heat loss can be very complex. Rabi [65] analyzed and reported formulas to calculate the heat transfer and heat loss coefficient of typical collectors.

Most of the theoretical models of nanofluid heat transfer coefficient are from traditional equations like the Dittus–Boelter equation [66] or the Gnielinski equation [67] with adding empirical parameters [64]. Thus, these equations are not valid for every nanofluid. In recent years, Polidori et al. [68] scrutinized the natural convection heat transfer of Newtonian Al_2O_3/H_2O nanofluids. Godson et al. [53] investigated experimental forces and natural heat transfer with nanofluids. They further used the mathematical modeling for convective heat transfer of nanofluids. Maxwell [53,69] found that the convection heat transfer and thermal conductivity improves by suspending micro-sized particles in a basefluid. On the other hand, adding these solid particles can cause rapid sedimentation, erosion, clogging and a high-pressure drop [53].

A brief and comprehensive overview of several experimental and theoretical studies on convection heat transfer of nanofluids is shown in Table 3 and Table 4 respectively.

The net radiation heat transfer rate for the solar collector, based on the surfaces involved in the system, as indicated in Fig. 1 is calculated as follows:

$$\dot{Q}_c = (H_c - B_c)A_c \tag{12}$$

where H_c is the incident radiation, B_c is the radiosity and A_c is the exposed solar collector surface area. Eq. (13) shows the radiation net heat transfer rate at the solar collector gray surface area [102,103].

$$\dot{Q}_c = \{\alpha_c I - e_c \sigma (T_c^4 - T_0^4)\} A_c \tag{13}$$

3.4. Efficiency

The instantaneous efficiency η of a solar thermal collector is defined as the ratio of the useful heat delivered per aperture area and the insulation, which is incident on the aperture:

$$\eta = \dot{Q}/AI = \dot{q}/I \tag{14}$$

Table 4
Summary of the theoretical studies on convective heat transfer of nanofluid.

Author	Theoretical investigations	Approach	Results and remarks
Xuan and Li [91]	Theoretical heat transfer characteristics of transformer oil–Cu and water–Cu nanofluids	Single phase fluid approach	Significant enhancement of heat transfer coefficient with decreasing the particle size (and not only due to thermal conductivity increase)
Xuan and Roetzel [59]	Heat transfer of nanofluid	1. Single phase fluid approach 2. Dispersion model approach	Suspended particles boost up the thermal conductivity Chaotic movement of ultrafine particles and the thermal dispersion accelerates the energy exchange process
Maiga et al. [92]	Forced convection flow of nanofluid (water/Al_2O_3 and ethylene glycol/Al_2O_3) in a circular tube	Single phase fluid approach	60% enhancement in HTC was found and turbulent flow enhancement increases with *Re*
Roy et al. [93]	Hydrodynamic and thermal flow fields of water/Al_2O_3 nanofluid in a radial laminar flow cooling system		Two times increase in heat transfer coefficient was detected along with wall shear stress and particle concentration
Ding and Wen [94]	Effects of particle migration in laminar flows of nanofluid	Mass conservation laws and momentum balance	Shear induced migration, viscosity gradient migration and self-diffusion. Highly nonuniform thermal conductivity profile obtained
Buongiorno [95]	Convective transport in nanofluid	Two-component nonhomogeneous equilibrium model	Brownian diffusion and thermophoresis are the two most considerable nanoparticle-basefluid slip mechanisms
Maïga et al. [96]	Forced convection flow of nanofluid (water/Al_2O_3 and ethylene glycol/Al_2O_3) in a circular tube and radial channel between a pair of parallel coaxial discs	Single phase fluid approach	HTC increased by 63 and 45%. Increased heat transfer and dynamic viscosity resulted in increased wall shear stress with partial loading
Palm et al. [97]	Heat transfer capabilities and temperature dependant properties of nanofluids in radial flow cooling systems	Single phase fluid approach	Temperature dependent properties lead to greater heat transfer predictions with the decrease in wall shear stresses
Kim et al. [98]	Thermo diffusion (Soret effect), diffusion thermo (Dufour effect) effects in binary nanofluids	One fluid model	As the Soret and Dufour effects the convective motion in nanofluids sets in easily
Behzadmehr et al. [99]	Turbulent forced convection flow in a uniformly heated tube	Two phase mixture model	HTC enhances with *w* and *Re*. Higher *Re* resulted in more uniform velocity profile
Mansour et al. [100]	Thermal and hydrodynamic performance for both laminar and turbulent forced convection in a tube with uniform heat flux at the wall	Single phase fluid approach	Both the models predicted increased HTC with particle concentration
Prakash and Giannelis [101]	Thermal conductivity of Al_2O_3 Nanofluids using temperature and concentration dependent viscosity		Thermal conductivity is dependent on the size of the nanoparticle, temperature viscosity and particle concentration

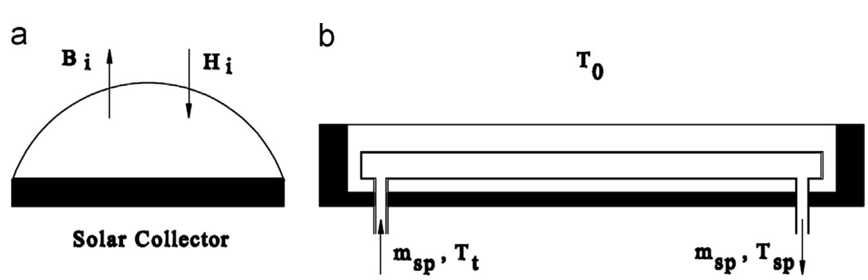

Fig. 1. (a) Thermal radiation energy interactions on the solar collector surface and (b) solar collector details.

Furthermore, collector efficiency in other words is useful heat gain per incident solar energy over the same period:

$$\eta = \int Q_u dt / A_c = \int G_T dt \tag{15}$$

The useful heat is related to flow rate, specific heat at constant pressure, and inlet and outlet temperature:

$$\dot{Q} = \dot{m} C_p (T_{out} - T_{in}) \tag{16}$$

The efficiency may depend on many factors, e.g., collector temperature, ambient temperature, insulation, flow rate, and incident angle [65].

Based on literatures, there are two different efficiencies: one acquired from experimental data (Eq. (17)), and the other from the implementation of a model (Eq. (18)).

$$\eta_{EXP} = \frac{Q_{useful-EXP}}{G_T A_{CO}} = \frac{\dot{q}_{co}\rho_w C_p (T_{out.co} - T_{in.co})}{G_T A_{co}} \tag{17}$$

$$\eta_{MOD} = \frac{Q_{useful-MOD}}{G_T A_{CO}} = \frac{\dot{q}_{co}\rho_w C_p (T_{out.co} - T_{in.co})}{G_T A_{co}} \tag{18}$$

Practically, the efficiency of a solar collector is a function of the fluid temperature, and not absorber temperature, thus the equation is simplified as follows [65]:

$$\eta = F_m\{\eta_0 - U(T_m - T_{amb})/I\} \tag{19}$$

where $T_m = (T_{in} + T_{out})/2$ and F_m is a collector parameter that accounts for the heat transfer from the absorber surface to the fluid, also is called collector efficiency factor or heat transfer factor. In a characteristic manner, the collector efficiency is in the range of 0.8–0.9 for non-evacuated air collectors, 0.9–0.95 for non-evacuated liquid collectors, and 0.95–1 for evacuated collectors.

O'Brien-Bernini and McGowan [104] found that semitransparent and transparent plates and absorbent fluid increase the efficiency of low to medium temperature application collectors.

Otanicar et al. [105] found that heat is transferred by a small area of nanofluid in direct absorption solar collector, which is closer to the center of the fluid. Therefore, this can prevent heat lost from the surface to the environment and improve the efficiency.

In recent years, the number of experimental works on the implementation of nanofluid in solar collectors has increased due to the lack of real information in this application, while the total number of works is limited and need further research. Different mixtures of water and nanoparticles have been examined in different types of solar collectors. Experimental investigations on CuO/water have been done in direct absorption solar collector and the results showed the ability of up to 30% improvement in the heat transfer coefficient compared to the basefluid [106–108]. Three different experiments were conducted by Yousefi et al. [109–111] to find the effects of using Al_2O_3 and MWCNT in a flat plate water based solar collector. Aluminum oxide nanoparticle with 0.2 wt% showed improvement in overall efficiency by around 28%, but this amount was decreased to around 15% in case of using surfactant. Contrariwise, the efficiency was reduced using 0.2 wt% MWCNT, while 0.4 wt% of the same nanoparticle improved the efficiency at the same condition. Theoretical investigations on the effects of aluminum/water nanofluid have revealed that the solar radiant absorption ability of basefluid is improved by adding aluminum nanoparticle to the base fluid [20,112–114].

Table 5 presents a summary of the reviewed experimental and theoretical works done by different authors for different types of solar collector along with the nanofluid types and results.

3.5. Environmental performances

From the environmental point of view, the performance of solar collectors presents clean, renewable, and available energy, which is essential for sustainable development. Solar collectors as a kind of solar energy devices are clean energy producers during their operation. Solar energy technologies such as solar collectors provide significant environmental advantages due to reducing fossil fuel consumption and as a result reducing global warming, greenhouse effect, climate change, Ozone layer depletion, and acid rains [126].

The US EPA (Environmental Protection Agency) has used solar environmental benefits calculator and computed that if a small solar heat water system (250 l capacity) was installed in Iowa, emission of 8.2 kg NO*x*, 16.8 kg SO_2, and 3876.0 kg CO_2 would be avoided annually [127].

Since the environmental advantages of solar technologies are relatively huge, it is possibly less critical to take a look at the small amount of pollution that is produced due to the production and transportation of solar technologies [127]. Solar collector technologies have also negative impacts on environment. These environmental impacts include operational and before operational impacts. Solar collectors have no direct pollution during operation, just they have indirect pollution due to the maintenance activities such as using vehicle to access and replace the heavy equipments. Other impacts due to using collectors include visual impacts, noise intrusion (depending on the solar technology used such as pumps, solar tracking devices, and switchgear noise), washing collectors, etc. Solar collectors have also negative impacts on environment before operation including huge impacts during production process such as air pollution, land pollution, water pollution, and noise and also during transportation such as air pollution, noise, etc. [126,127].

A comprehensive analysis of the environmental performance of solar collectors during its whole life cycle (the production stage, the distribution system and the product disposal and incineration) shows that it is not absolutely clean. This is called “hidden” impacts. Battisti and Annalisa [128] found that, from an environmental point of view, the contribution of distribution and disposal stages impacts less than 2%. On the other hand, the highest impacts occur during the production phase. A life cycle assessment (LCA) is an approved methodology that can be used to evaluate the environmental and cost impact of a solar collector. It also helps to enhance its global environmental performance [125,128]. Authors also found that the environmental payback time values are notably lower than the expected lifespan of the system [128].

It is evident from the foregoing discussion that the most important factor to improve environmental performance of solar collector is effort to achieve manufacturing environmentally friendly industrialization and to make a usage/production balance between economical and the environmental production.

3.6. Economical analysis

The choice of specific materials for a solar collector system is based on a trade-off analysis of cost and performance. The design of a solar energy system is concerned with obtaining minimum cost of any energy for delivery process including all of the items of hardware and labor that are involved in installing the equipment plus the operating expenses. Thus, it may be desirable to design a collector with an efficiency lower than the amount that is technologically possible if the cost significantly reduces [30]. Production of nanofluids requires advanced and sophisticated equipments, which needs additional investment. However, these high price equipments do not necessarily increase the nanofluid's production costs. Since only a small amount of nanoparticle is added to the basefluid (around 1%), the final price of nanofluid will not be very significant [129,130].

Solar processes are generally known to have high initial cost and low operating cost. Other factors to consider are the interest on money, borrowed, property and income taxes, resale of equipment, maintenance, insurance, fuel, and other operating expenses. The objective of the economic analysis can be viewed as the determination of the least costly method of meeting the energy need. Several economic criteria have been used for evaluating and optimizing solar energy systems. These include the possible figures of merit: least cost effective solar energy, life cycle costs

Table 5
Summary of nanofluid base works on solar collector application.

Author	Type of investigation	Nanofluid	Particle size and fraction	Collector type	Results and remarks
He et al. [106]	Experimental	CuO/deionized water (surfactant)	D=25,50 nm, 0.01,0.02, 0.04,0.1, 0.2 wt%	Direct absorption solar collector	– The transmittance decreases with increasing nanoparticle size, mass fraction and optical depth collector – Cu–H_2O nanofluid has good absorption ability for solar energy, and less transmittance compared with deionized water
Liu et al. [108]	Experimental	CuO/water	D=50 nm 1.2 wt%	Evacuated tubular solar air collector	– The maximum and mean value of the collecting efficiency of the collector with open thermosyphon can increase 6.6% and 12.4% in case of using nanofluid, respectively
Risi et al. [115]	Numerical	(CuO+Ni)/nitrogen gas	0.01–0.3 vol%	Parabolic trough collector	– Maximum solar to thermal efficiency is 62.5% ($T_{\text{out, nanofluid}}=650\ ^\circ C$) – Above 0.3 vol% the drawback effect of pressure drop overwhelm the beneficial effects of thermal properties
Nasrin et al. [116]	Numerical	Alumina/water	5.0 vol%	Glass cover plate with sinusoidal absorber	– The effect of higher Pr on enhancing performance of heat transfer in Al_2O_3 is more than base fluid – The rate of convective heat transfer improves by 26% and 18% for Al_2O_3/water and water respectively with the increasing values of Pr from 1.73 to 6.62 – The radiation enhances rate is just 8% in the same condition
Nasrin et al. [117]	Numerical	Alumina/water	5.0 vol%	Glass cover plate with sinusoidal absorber	– Convective heat transfer rate improves by 19% and 12% for the nanofluid and base fluid, respectively – Average heat transfer obtained is higher for convection than radiation
Tiwari et al. [118]	Theoretical	Al_2O_3/water	0.5–2 vol%	Flat plate	– Thermal efficiency increases 31.64% by using the 1.5 vol% Al_2O_3 – Al_2O_3/water (1.5 vol%) has potential to decrease 31% $kgCO_2$/kWh
Yousefi et al. [109]	Experimental	Al_2O_3/water (Surfactant: Triton X-100)	D=15 nm, 0.2 and 0.4 wt%	Flat plate	– 28.3% efficiency improvement was achieved by using 0.2 wt% nanoparticle – The maximum efficiency enhancement is 15.63% in case of using surfactant
Yousefi et al. [110]	Experimental	MWCNT/water (surfactant: Triton X-100)	D=10–30 nm, 0.2 and 0.4 wt%	Flat plate	– Efficiency of the collector increases remarkably for 0.4 wt% nanofluid, whereas with 0.2 wt% the efficiency reduces compared to water – For 0.2 wt% nanofluid using surfactant the efficiency of the collector increases compared to water
Yousefi et al. [111]	Experimental	MWCNT/water	D=10–30 nm, 0.2 wt%	Flat plate	– A bigger difference of pH values with respect to the pH of isoelectric point leads to higher efficiency
Chougule et al. [119]	Experimental	CNT/water	D=10–12 nm and L=0.1–10 μ, 0.15 vol%	Flat plate	– The average collector efficiencies for water and nanofluid are 25% and 45% at 31.5° tilt angle – The average collector efficiencies for water and nanofluid are 36% and 61% at 50° tilt angle

Table 5 (*continued*)

Author	Type of investigation	Nanofluid	Particle size and fraction	Collector type	Results and remarks
Lenert and Wang [120]	Experimental & analytical	Carbon-coated cobalt/ Therminol VP-1	D=28 nm, 2.5–10⁎10^{-4} vol%	Concentrated solar collector	– Numerical modeling shows the receiver efficiency increases with increasing nanofluid height and incident solar flux
Saidur et al. [113]	Analytical	Alumina/water	D=1.0, 5.0, 10, 20 nm, 2 vol%	Direct solar collector	– The extinction coefficient is linearly proportionate to volume fraction. The effect of particle size on the optical properties of nanofluid is minimal
Khullar and Tyagi [112]	Theoretical	Alumina/water	D=10 nm, 0.01 vol%	Concentrating direct absorption	– Increase solar radiant energy absorption up to 99% – Achieved higher output temperatures
Khullar et al. [121]	Theoretical	Alumina/Therminol VP-1	D=5 nm	Concentrating parabolic	– The nanofluid concentrating parabolic solar collector has about 5–10% higher efficiency in the same external condition
He et al. [122]	Experimental	TiO_2, CNT/water	D=5–10 nm, D=10–50 and L=100–1000 nm	Vacuum tube	– CNT/water is more suitable than the TiO_2/water to be used in a vacuum tube solar collector
Li et al. [123]	Experimental	Al_2O_3, ZnO, MgO/water	$D<20$ nm	Tubular	– The best nanofluid for solar collector is ZnO/water with 0.2 vol%
Lu et al. [107]	Experimental	CuO/water	D=50 nm 0.8, 1.0, 1.2, 1.5 wt%	Evacuated tubular solar air collector	– The CuO nanoparticles has the potential to increase evaporation heat transfer coefficient by about 30% – The wall temperature of the open thermosyphon decreases due to use of the CuO nanofluid
Taylor et al. [124]	Experimental and theoretical	Graphite, alumina, silver, copper/Therminol VP-1	D=20 nm, 0.1 vol%	Concentrating direct absorption	– Nanofluid helps to improve efficiency by 5–10%
Otanicar et al. [105]	Experimental and theoretical	Graphite, silver, carbon nanotube/water	D=30,20 and 40 nm, D=20 and L=1–5⁎10^3 nm, 0.0–1 vol%	Non-concentrating direct absorption	– Efficiency increases 6% when the particle size halved from 40 nm in silver/water nanofluid – Optimum volume fraction is 0.5%
Tyagi et al. [20]	Theoretical	Alumina/water	D=0–20 nm, 0.1–5 vol%	Non-concentrating microscale direct absorption	– Efficiency exceptionally increases for nanofluid concentration up to 2 vol% and remains nearly constant for >2 vol% – Absolute efficiencies is around 10% higher in case of nanofluid
Otanicar and Golden [125]	Theoretical	Graphite/water+propylene glycol	0.1 vol%	Direct absorption	– Using a nanofluid-based solar collector leads to approximately 3% fewer CO_2 emissions compared to the conventional solar collector

(LCC), annualized life cycle cost (ALCC), payback time, and return on investment (ROI) [30,131].

4. Challenges of utilizing nanofluids

There are many challenges that engineers and researchers face in increasing overall performance of applicable systems; such as increase in durability, reliability, efficiency, safety, and decreasing initial cost, life cost, size, weight etc.

Theoretically, using nanofluid is beneficial to the heat transfer of the system. However, according to literature, nanofluids also have some disadvantages compared with basefluid. The disadvantages include decreased dispersion stability of nanoparticles with respect to time, increased viscosity of nanofluid due to adding particles to the fluid, increased pressure drop and pumping power due to the higher viscosity of nanofluid, lower specific heat of nanofluids, higher production cost of nanofluids due to the need for advanced and complicated equipments and the tendency to agglomeration into larger particles [22].

Overall performance is a function of nanofluid properties as well as the other properties of system. Interaction between each properties of nanofluid with other properties is complicated and considered.

5. Future directions

The proportion of using flat plate solar collectors to vacuum tube collectors in central Europe is around nine to one. Close to majority of thermal collectors are applied for tap water heating and supporting heating systems. Improvement of the combination methods of solar collectors and solar photovoltaic panels into buildings is one of the difficult challenges in the solar industry [132].

There are several important issues that should be taken into account as future challenges in this field such as: Brownian motion of particles, particle migration, changing thermophysical properties with temperature, tendency of nanoparticles to agglomeration, changing nanofluid properties by using additives, and stability of nanofluids [22].

Lack of study on optical properties of nanofluid in the solar collector and the other properties except the thermal conductivity is obvious and it needs more attention. Using nanofluid with mixture of more than one nanoparticle is a complicated and new field of research in this area.

6. Conclusions and recommendations

Solar collectors have a great potential for producing heat and are highly suited to be applied in water heater and air heating systems. Unique properties of nanofluids, due to the smaller size and larger surface area, make a massive evolution in heat transfer. Nanoparticles, as suspension particles into a liquid, have what it takes to change the physical and thermal properties of the basefluid. Therefore, by increasing energy transfer and decreasing energy losses, it can help to increase the performance and efficiency of solar collectors. This provides promising ways for engineers to improve highly effective green devices.

This paper presents an overview of recent studies in the performance of solar collector, especially direct solar absorption collector by using nanofluid as the working fluid. Despite the great effect of nanoparticles on changing optical properties of fluid, nanofluids have little considerable effect on performance of typical (non-direct) solar collector due to changing the optical properties of basefluid such as transmittance and extinction coefficient; but there is significant effect on optical properties of direct absorb solar collector.

According to the literatures, water is the best absorber in direct absorption solar collector due to its strong solar absorption, but it is not high enough (only 13% of the incoming energy). Suspension nanoparticles can improve the optical properties of basefluid, which are dependent on particle size, particle shape, the optical properties of the particle and basefluid. Extinction coefficient is a function of the particle diameter and wavelength of the light. Nanofluid with small diameter suspended nanoparticle has higher extinction coefficient compared with conventional basefluid therefore has more capability to absorb the energy from incident light in a solar collector.

Particle concentration, temperature, size, dispersion, and stability are the most effective parameters to increase the thermal conductivity of nanofluid. Thermal conductivity of metallic nanofluids is more than non-metallic nanofluid, while metallic nanofluids are less absorptive. The effect of surface to volume ratio in thermal conductivity is more than surface size of nanoparticles. The most important way to decrease the speed of nanoparticle sedimentation is to decrease the size of nanoparticle.

Several articles have investigated thermal conductivity of nanofluids to increase heat transfer, but the shortage of research to investigate the other properties of nanofluid such as the effect of Brownian motion and analysis based on two-phase fluid (suspended solid into liquid) is obvious and evident. Future research needs to focus on two-phase analysis of nanofluids in order to find more accurate relationships between properties of nanoparticles and nanofluid.

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